CONTRIBUTION OF ANIMAL MANURES TO THE INCREASE IN GREENHOUSE GASES AND ACTION TO REDUCE EMISSIONS

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INTRODUCTION

Human activity contributes to the atmospheric accumulation of gases which cause global warming. Concentrations of methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O) have risen by 115%, 26% and 7% respectively over levels of the preindustrial era (Steed and Hashimoto, 1995) and the increase is expected to continue if no mitigation action is taken (Johnson *et al.*, 1996). Thus the expected increases in CO_2 should produce 63% of the warming, followed by CH_4 at 20% and N_2O at 4% (IPCC, 1994). In global terms, agriculture accounts for about one-fifth of the forecast impact of the greenhouse effect caused by human activity, producing approximately 50% and 70% of all anthropogenic emissions of CH_4 and N_2O respectively (IPCC, 1996). The agricultural sector contributed about 4% of greenhouse gas (GHG) emissions for Canada as a whole in 1995 (Jacques, 1997), with the main sources considered to be enteric fermentation (55%), agricultural soils (24%) and manure (21%). This article deals with the third emission source, that is the emission of CH_4 from solid and liquid manures.

1. STATE OF CURRENT KNOWLEDGE

Livestock buildings and manure storage structures are fixed, permanent sources of various gas emissions (Hartung, 1994). Since animal digestive processes are incomplete, and because microorganisms are present in the faeces, there is a substantial amount of organic matter which can be converted to CH_4 when it decomposes in wet, anaerobic environments (Johnson *et al.*, 1996). These conditions are found, among other places, in manure slurry gutters and pits and in anaerobic lagoons. Manure is thus potentially a major source of GHG emission, primarily in the industrialized countries where a large proportion of livestock production is intensive (Moss, 1993). It is even estimated that in the coming decades CH_4 emissions will increase due to a rise in animal production combined with a greater use of liquid manure management systems (Gibbs and Woodburry, 1993). As early as 1992, this type of manure management accounted for 77% and 55% respectively of systems used in the pork and dairy industries in Eastern Europe, and for 50% and 23% respectively in the same industries in North America (Safley *et al.*, 1992). Moreover, because of the lengthy storage periods made necessary by environmental and legal requirements in North America and Europe, the conditions allowing anaerobic degradation also tend to last longer. In spite of this, the task of assessing CH_4 emissions from manure has been neglected until recently (Steed and Hashimoto, 1995; Husted, 1993; Patterson, 1989).

1.1 Recent assessments of GHG emissions from manure.

1.1.1 Nitrous oxide

There is little information on the exact amounts of N_2O emitted by manure. However, we know that nitrous oxide is an infrared absorber with significant potential for atmospheric warming, exceeding that of CO_2 by a factor of 300 (Kroeze, 1998). If no steps are taken to reduce emissions, the N_2O concentration could more than double over the next century.

Manure is a source of N_2O emission because part of its nitrogen content can be converted to N_2O by microorganisms during storage and/or after spreading. The partial oxidation and volatilization of nitrogen from manure account for about 43% of N_2O emissions in agriculture, while the use of chemical fertilizers contributes 44% (Johnson *et al.*, 1997).

Petersen *et al.* (1998) assessed nitrogen losses through volatilization of ammonia, N_2O emissions and nitrogen leaching from pig and cow manures stored in solid form for 9 to 14 weeks in the spring and fall. They discovered that in all cases, N_2O emission was less than 2% of the nitrogen losses from denitrification (13 to 33% of total losses). Another significant source of nitrogen loss from solid or liquid manure affecting N_2O emissions is the volatilization of ammonia (NH_3). The volatilization of NH_3 from manure storage structures can cause the unintentional fertilization of the surrounding land and lead to further N_2O emissions from the soil (Duxbury, 1994). This indirect source of N_2O emission is more difficult to assess and quantify. Atallah *et al.* (1995) have also discovered that solid storage with or without composting gives rise to a combination of factors (high heat, pH and inorganic N concentration) which influences ammonia volatilization substantially. Finally, Hüter *et al.* (1997a) have stated that N_2O emission depends more on the area of contact of the manure pile with the ambient air than on the amount of manure stored.

1.1.2 Methane

Few experimental findings are available on the precise CH_4 emissions resulting from the various types and conditions of farm manure storage, and the existing data reflect fairly significant uncertainties. The estimates made in the 1990s on global CH_4 emissions vary between 10 Tg/year (Gibbs and Woodburry, 1993) and 35 Tg/year (Safley *et al.*, 1992; Steed and Hashimoto, 1995) for animal manures of all kinds. After certain adjustments in methane conversion rates according to temperature and type of storage, global CH_4 emissions appear to be in the vicinity of 10 to 14 Tg per year (EPA, 1994). On the other hand, Husted (1994) notes that most of the results reported are based on studies of biogas production in covered anaerobic slurry tanks, and that quantitative measurements were often made in closed chambers. These measuring systems can lead to erroneous results in determining gas emissions, as shown by Jackson *et al.* (1994) and Matthias *et al.* (1978).

Accordingly, Husted (1993) assessed CH_4 emissions from storage structures for liquid and solid pig manure using dynamic measurement chambers. The results showed a major spatial variation in the emission rate between different sampling points. For liquid manure, the CH_4 emission rate varied between 0.5 and 41.7 g $CH_4m^{-3}d^{-1}$ and for solid manure the variation was between 0.6 and 34.3 g $CH_4m^{-3}d^{-1}$. The author explains the phenomenon by the presence of hot spots of methanogenesis with greater amounts of organic matter which can be decomposed by methanogenic bacteria. He also notes that the emissions vary as a function of storage operations (agitation and handling) and storage conditions (i.e. slurry temperature and volume). The author concludes that a valid assessment of annual CH_4 emissions from storage structures cannot be done with a few seasonal samplings.

Husted (1994) then monitored CH_4 emissions from liquid and solid pig and cow manure over a one-year period. The monthly emission averages he obtained varied widely, and releases from liquid manure were low in winter and high in summer. As a result of this monitoring procedure, the author determined the average annual release of CH_4 to be 11.6 g $CH_4m^{-3}d^{-1}$ for pig manure slurry (2% solids), 8.2 g $CH_4m^{-3}d^{-1}$ for cow manure slurry (6.5% solids), 28.3 g $CH_4m^{-3}d^{-1}$ for solid pig manure (22.9% solids) and 5.9 g $CH_4m^{-3}d^{-1}$ for solid cow manure (18.7% solids). According to these results, stored solid manure containing a high proportion of bedding materials (solid pig manure) showed higher annual CH_4 emission rates than liquid pig manure for the period under study. The aerobic microbial activity occurring on the sides of the manure pile maintains higher temperatures which enhance the methanogenesis taking place within the manure pile. This phenomenon has also been observed by Petersen *et al.* (1998), who report an increase in CH_4 concentration inside pig manure piles over a relatively long storage period. Another interesting discovery of Husted's study (1994) is that the slurry temperature never went below 4°C despite ambient temperatures below the freezing point. This indicates that there is a potential for CH_4 production throughout the year in Denmark. Moreover, the author notes that the formation of a crust on the surface of the manure slurry considerably reduces CH_4 emission, although he does not give any potential explanations for this reduction. On the basis of his results, Husted (1994) concluded that CH_4 production in Denmark is about 80% less than earlier assessments. He explains this phenomenon by the large variations in seasonal emissions and quantity stored, as well as by the formation of a surface crust in slurry storage structures. The impact of this last factor is questionable, however, since the natural crust which forms at the surface of the slurry in storage tanks is generally porous and provides almost no resistance to the diffusion of methane, the solubility of which is very low. On the other hand, a possible explanation for the decrease in methane emissions is that oxygen and microorganisms present in the porous crust oxidize the methane to CO_2.

For their part, Steed and Hashimoto (1995) undertook to determine CH_4 emissions resulting from various methods of managing dairy cattle manure. In the laboratory, they reproduced the normal storage conditions found in different management systems: depositing of manure by animals on pastureland (14% solids, exposed to air); storage in solid form in a pile (14% solids, not exposed to air); and liquid management (9% solids, not exposed to air). The tests were run at three storage temperatures (30, 20 and 10°C) over periods of more than

130 days. On the basis of the volumes of gas produced and CH_4 concentration, the authors determined CH_4 conversion factors for the different storage systems to compare them with existing data (Safley *et al.*, 1992). According to the results obtained by Steed and Hashimoto (1994), some of the management systems most widely used throughout the world produce less than had been previously determined, while the management systems which are less prevalent worldwide, although common in the industrialized countries, produce more than expected. For example, the emission of CH_4 from manure deposited in the field by animals is less than one-fifth of the values reported. This agrees with the results of William (1991) and Johnson *et al.* (1997), who report that CH_4 emission from cow excrement on pastureland is low because drying and airing inhibit methanogenesis. Conversely, emission from solid storage is 6.5 times higher and, from liquid storage, 3.8 times higher at high temperatures (30°C). However, the authors also report that a negligible amount of methane is produced at 10°C. Worldwide, their assessment of 35.2 Tg of global CH_4 emission per year agrees with the figure of 28.3 Tg CH_4 per year obtained by Safley *et al.* (1992). On the other hand, in determinations of methane production on a smaller scale, Safley *et al.* (1992) report a value of 1,013,428 Mg/year for the U.S. dairy industry, while according to Steed and Hashimoto (1994) that figure is 356,682 Mg CH_4/year. This value is closer to the estimate by Lodman *et al.* (1991) of about 382,000 Mg/year, where the emission rate was adjusted according to storage conditions. Steed and Hashimoto (1994) took storage temperature into account in their determinations for the U.S., and they think the global value would also be lower if special attention were paid to the storage temperature for each region.

Some studies have also been carried out to check the applicability of CH_4 emission assessments for livestock conditions in Canada. Patni *et al.* (1995) determined that CH_4 emission from a liquid manure storage structure for dairy cattle (9% solids) was 1.19 g $CH_4m^{-3}d^{-1}$ for a summer period (ambient temperature of 6 to 30°C) of 188 days. This value is about 15% of the annual average reported by Husted (1994). The lower ambient temperature was probably the reason for this pronounced difference. A concurrent assessment of CH_4 emission from a storage system in the laboratory indicated that smaller-scale testing is a good reflection of results obtained on the farm (Jackson *et al.*, 1994). Other laboratory studies were subsequently undertaken (Massé and Patni, unpublished) to quantify CH_4 emission from pig and cow slurries for different storage temperatures and solids content values, and with storage periods varying between 275 and 350 days. For pig manure slurry with a low solids content, CH_4 emissions were about 3.8 g $CH_4m^{-3}d^{-1}$ and 21.6 g $CH_4m^{-3}d^{-1}$ at 10 and 15°C respectively. For pig slurry with a high solids content, average emission rates varied between 11.7 g $CH_4m^{-3}d^{-1}$ and 19.5 g $CH_4m^{-3}d^{-1}$ at 10 and 15°C respectively. These results show that the temperature and solids content influence the CH_4 emission rate for pig manure slurry. For cow manure slurry, CH_4 emissions are lower than for pig slurry, but the variations due to solids content or storage temperature are still relatively substantial. For a high solids content, methane emissions varied between 0.7 and 1.0 g $CH_4m^{-3}d^{-1}$ at 10 and 15°C respectively, which agrees with the values reported by Patni *et al.* (1995). For slurry with a low solids content, however, the data obtained varied between 0.5 and 6.4 g $CH_4m^{-3}d^{-1}$ at 10 and 15°C respectively. The high emission rate at 15°C can be linked to a marked rise in biogas production between 175 and 350 days of storage. This significant increase may result from adaptation of the methanogenic microorganisms under

these conditions. The presence of inhibitory compounds in higher concentrations (i.e. NH_4^+, organic acids) could have delayed the phenomenon in the solid manure which was high in solids content, since the increased biogas production began only after 300 days of storage. Finally, the low temperature seems to have prevented the phenomenon in the other cases.

Table 1 shows the results of the most relevant studies on rates of methane emission from solid pig and cow manure under livestock production conditions found in Canada. It is difficult to apply all these values and to accurately determine the actual CH_4 emissions from various types of manure storage. A number of external factors (physicochemical properties of the manure, method of measuring gas emission, temperature variation profile, amount of manure, fraction available for microbial degradation, age of the manure, formation of a crust on the surface of manure slurry, and so on) can influence CH_4 production, and these parameters were not monitored in the same way or even taken into consideration in all studies. On the other hand, we can see that the data seem to have the same order of magnitude and that there is indeed significant variability in the reported results on CH_4 emissions from manure. The emission of CH_4 is greater for pig manure and, contrary to what we might think, can be greater for storage in solid form (Husted, 1994). Results obtained by Ahlgrimm and Breford (1998) in a long-term study of several livestock production systems for fattening hogs also seem to indicate that liquid manure management emits less CH_4 than deep-litter livestock systems.

Table 1. Average rate of CH_4 emission from dairy cattle and pig manure stored under different experimental conditions

Storage temperature (°C)	Solids content (% TS)	Storage period (days)	CH_4 emission ($g\ CH_4\ m^{-3}d^{-1}$)[a]	Reference
Pig manure				
10	5	271-273	3.75 (3.21 - 4.51)	Massé and Patni, unpublished
10	17	271-273	11.69 (9.41 - 12.93)	Massé and Patni, unpublished
15	5	271-273	21.58 (15.80 - 28.69)	Massé and Patni, unpublished
15	18	271-273	19.45 (17.16 - 25.84)	Massé and Patni, unpublished
Variable (-5 to 25)	2	365	11.6 (0.4 - 35.8)	Husted, 1994
Variable (-5 to 25)	23	365	28.3 (0.4 - 142.1)	Husted, 1994
Cow manure				
10	9	306-335	0.67 (0.55 - 0.78)	Massé and Patni, unpublished
10	4	306-335	0.51 (0.49 - 0.52)	Massé and Patni, unpublished
15	9	305-308	1.02 (0.97 - 1.20)	Massé and Patni, unpublished
15	4	305-308	6.37 (4.72 - 8.45)	Massé and Patni, unpublished
Variable (14-23)	9	188	1.19	Patni *et al.*, 1995
Variable (-5 to 25)	6.5	365	8.2 (0.0 - 34.5)	Husted, 1994
Variable (-5 to 25)	18.7	365	5.9 (0.1 - 42.7)	Husted, 1994

[a] The values in parentheses indicate the data spread.

2. ACTION TO MITIGATE GHG EMISSIONS

Conventional methods for managing and storing manure in liquid or solid form are inescapable sources of GHG emissions. If no reduction measures are taken, the increase in animal production will lead to a rise in the gas emissions linked to the management of manure produced by livestock. However, a number of avenues could be followed to stabilize and even reduce greenhouse gas emissions (Gibbs and Woodburry, 1993). In agricultural environments, technological approaches should concentrate mainly on CH_4 and N_2O emissions. After discussing ways to decrease N_2O emission from manure, we will therefore describe some possible measures for reducing CH_4 emissions.

2.1 Physicochemical methods of reducing GHG emissions

Certain simple methods can reduce NH_3 emissions which might result in the indirect fertilization of surrounding land and the production of N_2O. First of all, there is acidification of the manure. The addition of products of organic or chemical origin, such as peat moss, sulphuric acid, phosphoric acid, lactic acid or nitric acid, results in a lowering of pH and reduces the volatilization of ammonia (Al-Kanani *et al.*, 1992; Berg and Hörnig, 1997; Kroodsma and Ogink, 1997). At the same time, acidification of manure slurry can give rise to other problems such as the volatilization of H_2S. If the process is used inside buildings, it can involve a health risk for workers. Moreover, such control of NH_3 emissions by acidification can increase CH_4 and N_2O emissions (Kroodsma and Ogink, 1997) by creating conditions which speed up denitrification (Gurk *et al.*, 1997; Kroodsma and Ogink, 1997). In addition, spreading solid or liquid manure that is more acidic might possibly influence the chemistry of soils and change the dynamics of trace element exchange in the plant-soil-water system, which would affect the growth or development of crops. However, Berg and Hörnig (1997) report that spreading manure slurry which had been acidified (pH 4.0) with lactic acid did not reduce soil pH and had no significant effect on crops in the short term. Nevertheless, no mention is made of initial pH or of soil alkalinity. It would therefore be important to verify the potential medium-term and long-term impact of this practice on different soil types and to determine its effects on plants, as well as on soil microorganisms, some of which reduce methane emissions by oxidizing it to CO_2.

Clemens *et al.* (1997) report that the reduction in ammonia volatilization during storage does not automatically result in an increase in N_2O emission when spreading. Even so, it would be necessary to quantify the actual reduction in emissions of nitrogen as NH_3 or N_2O for the overall manure management operation (from pit to spreading) to ensure that the problem is not merely shifted elsewhere and that nitrogen preserved in the slurry will not be released in the field.

One alternative to the acidification of manure slurry to minimize gas emissions is cooling. In fact, temperature has a direct effect on microbial activity in manure slurry and on the rate of ammonia emission. Systems developed recently in the Netherlands have made it possible to reduce ammonia emissions from a hog house by up to 75% (Brok and Verdoes, 1997). However, the system was complex and relatively expensive, and its application in Canadian animal

production establishments would be difficult to promote. The process would have to be modified to simplify its operation and reduce its cost. It would be enough to embed pipes in the walls and floor of the gutters and circulate outside air through them to cool the slurry to the desired temperature to reduce microbial activity and gas emissions. For new facilities, the pipes could be placed right in the concrete, while for existing buildings a pipe network could be installed at the bottom of the gutters and then covered by concrete so as not to interfere with the discharge of solid matter. The intake of air would have to be controlled to prevent freezing of the slurry and avoid damage to the structures during the coldest months.

Another simple but effective method of minimizing emissions of NH_3, and indirectly of N_2O, is to place covers on slurry storage pits. Covers reduce or stop air movements at the surface of the slurry, causing an increase in NH_3 concentration at the surface. The dynamic equilibrium established between the liquid and gas phases reduces the transfer of dissolved ammonia to the gas phase. However, information about the effect of such devices on the emission of other GHGs is contradictory. Some studies report that installing a cover could increase methane and nitrous oxide emissions (Hüter *et al.*, 1997), while other authors report no significant impact on CH_4 emission (Williams and Nigro, 1997). According to Hüter *et al.* (1997), porous covers (i.e. the natural crust or covers made of straw) create a larger aerobic zone at the surface and allow faster nitrification. Such nitrification would then provide a more abundant substrate for denitrification and the emission of N_2O through this process. Nevertheless, installing a completely airtight cover would allow recovery of all the biogas, which could be burned or treated to reduce GHG emissions.

In any event, the most promising avenue for the reduction of N_2O emissions does not seem to lie in the area of manure storage. A better solution would be to improve the fertilizing value of organic fertilizers (Kroeze, 1998). In fact, an increase in the agronomic effectiveness of manures would reduce the spreading rate, which has a direct effect on N_2O emission (Chang *et al.*,1997). The principle underlying this practice is that, if nitrogen added to crops is in a form which is more readily available to plants, the proportion available to soil microorganisms for nitrification and denitrification, and consequently for the production of N_2O, will be smaller (IPCC, 1996). Furthermore, a reduction in the spreading rate could have other indirect effects on the emission of other GHGs, as it might reduce the inhibitory effects of this practice on the activity of soil bacteria which oxidize CH_4 (Hutsch, 1998). Finally, if nitrogen from manure were used as efficiently as possible, the use of chemical fertilizers would be minimized, as well as the consumption of the fossil fuels required for manufacturing and transporting those fertilizers (Johnson *et al.*, 1997).

2.2 Biological methods for reducing GHG emissions

Biological methods for reducing emissions primarily apply to methane. Emissions of this gas from manure should be either minimized or else maximized to allow subsequent use of the biogas (Zeeman, 1994). Various biotechnologies are currently available for industrial farms, considered the main sources of emissions (Gustavsson *et al.*, 1998). One of the options available for reducing CH_4 emissions is the use of aerobic bioreactors. These biological systems for treating solid manure or slurry eliminate the anaerobic conditions which enhance CH_4 production, while reducing the organic load of the manure slurry and eliminating odours. However, this type of treatment increases the emission of N_2O following the oxidation of NH_4^+, and up to 20% of the nitrogen from manure can be released as nitrous oxide (Burton *et al.*, 1993; Wilters *et al.*, 1996; Pahl *et al.*, 1997; Driemer and Van den Weghe, 1997). The N_2O is released during the incomplete processes of nitrification and denitrification which occur during the treatment. The amount of N_2O produced is directly related to the concentration of dissolved oxygen in anaerobic bioreactors (Driemer and Van den Weghe, 1997). In the opinion of some authors (Sibbesen and Lind, 1993), a limited availability of oxygen could lead to the reduction of oxidized nitrogen compounds (NH_2OH, NO_2^-) during the nitrification process, and a portion of the N_2O could then be generated by incomplete nitrification. The emission of N_2O by nitrification has been demonstrated in soils (Bremner and Blackmer, 1978), and the phenomenon may also occur in manure. Moreover, insufficient nitrification caused by a limited oxygen supply during treatment would shift the problem to spreading. This is why an adequate level of oxygenation must be maintained to ensure complete nitrification. On the other hand, oxygen would inhibit the N_2O-reductase of denitrifying bacteria and N_2O would be released as the final product of denitrification instead of N_2 (Driemer and Van den Weghe, 1997). However, this source of N_2O emissions could be less significant than we think. Indeed, Pahl *et al.* (1997) mention that, in the presence of molecular oxygen, the metabolism of nitrifying bacteria would shift toward the respiration of oxygen, which is more efficient in terms of energy. The relative importance of the nitrification and denitrification processes which can take place during aerobic treatment is thus ambiguous. In certain cases, N_2O production can nevertheless reach 2 kg per cubic metre of manure slurry treated. At the same time, the aeration required for this treatment speeds up the volatilization of ammonia by direct desorption.

Composting of solid manures is another treatment which puts to good use the activity of aerobic microorganisms. As in the aerobic treatment of manure slurry, the processes of nitrification and denitrification occur simultaneously depending on the oxygen concentration in the different parts of manure piles. Again, there must be adequate aeration to ensure complete nitrification and to prevent denitrification as much as possible. With sufficient aeration, N_2O and CH_4 emissions can be reduced significantly (Boxberger *et al.*, 1997; Osada *et al.*, 1997; Hüter *et al.*, 1997b). However, all studies report a rise in NH_3 emissions with any increase in aeration.

A second option is the use of existing technologies which to maximize CH_4 production and recovery. These technologies would reduce methane emissions by 25 to 80% (Johnson *et al.*, 1996). The main technologies available are covered anaerobic lagoons and anaerobic digesters.

These systems provide anaerobic microorganisms with conditions allowing a more complete, efficient degradation of organic matter. Such controlled anaerobic digestion reduces the environmental and public health problems linked to manure management. In addition, these technologies allow recovery of the biogas, an energy source lost in conventional manure management systems.

The treatment of manure slurry in lagoons is generally used in large intensive production operations (Hogan, 1993). This type of treatment requires dilution of the solid manure in a considerable amount of water, which increases the volumes to be managed. The efficiency of the systems is closely tied to the weather conditions, since the installations are outside the buildings. More than one lagoon is generally required, and the ratio of area to volume of the systems is high, so the space needed to set up this type of treatment is substantial. Lagoons are more common in the United States, where temperatures are milder. In Canada, these systems might not operate in winter because the high area-to-volume ratio would allow the lagoons to cool and even to freeze.

Anaerobic bioreactors or digesters were developed to speed up the anaerobic decomposition of organic matter and to maximize energy and protein recovery. Accordingly, digesters were designed to function at mesophilic temperatures (30 to 40°C) or thermophilic temperatures (45 to 65°C). The manure had to be heated and the energy required to maintain the temperature of the digester in winter could exceed the energy produced from the biogas. In addition, the digesters were difficult to control, and qualified operators were required to run the systems. For these reasons, the digesters were not economically viable, since the capital investment was too high and the control and maintenance of such systems were painstaking. On the other hand, laboratory research has shown that a significant amount of CH_4 can be produced at ambient temperatures (Massé *et al.*,1997; Zeeman, 1994; Massé *et al.*, 1993). Wellinger and Kaufman (1982) note, moreover, that the drawbacks of mesophilic and thermophilic biogas production can be overcome by fermentation at ambient temperatures with a longer hydraulic retention time.

2.3 Low-temperature anaerobic digestion

Low-temperature anaerobic digestion seems much more appropriate for Canadian farms. Indeed, a system operating at low temperature does not involve any heating of the slurry before feeding to the digester. Moreover, the digester should contain a broader variety of microorganisms, as few are resistant to high temperatures, and the stability of the system would thus be increased. However, the agricultural industry will not be interested in the treatment of manure slurry to reduce its harmful effects on the environment unless the process can be implemented at low cost, is stable and easy to run, requires a minimum of qualifications and does not interfere with regular farm operations. It is with these objectives in mind that research has been carried out for a number of years at the Research and Development Centre of Agriculture and Agri-Food Canada in Lennoxville for the purpose of developing an economical process that is simple and easy to apply to the treatment of pig manure slurry. The treatment is based on the

anaerobic digestion at ambient temperatures of organic matter in a sequencing batch reactor (SBR) (Massé, 1997).

SBRs are characterized by their simplicity of operation, and their primary function is to provide the optimum conditions required for the anaerobic digestion of liquid manure. The system developed provides ideal conditions for retaining a large number of slow-growing microorganisms in the tank. Indeed the laboratory tests have shown that the system is very stable and flexible, and that it operates very well at low temperatures (between 10 and 20°C). In addition, the bioreactors need only be fed once a week, allowing farmers to perform this operation when cleaning the building. The process would therefore not interfere with the daily operations of the enterprise and would require little capital expenses, since it would use the slurry handling infrastructures already in place.

2.3.1 Ecological benefits of psychrophilic anaerobic digestion

The environmental benefits of this biotechnology are very attractive. The experimental results show, among other things, that the process deodorizes and stabilizes pig manure slurry by reducing the organic pollution load by 70 to 90%. It allows the deodorization of slurry through the degradation of most of the compounds comprising the 150 odorous volatile substances released by manure slurries. Furthermore, the substantial reduction in the organic load of the effluent produced provides protection for surface water by lessening the potential for runoff pollution. The technology also allows mineralization of fertilizers such as nitrogen and phosphorus, making them more available to plants and less subject to leaching when the treated slurry is spread on fields. This is important in the strategy of reducing fertilizer use to minimize N_2O emissions. Since the process increases the availability of nutrient elements to crops, the requirements in mineral fertilizers will be decreased. As we mentioned earlier, reducing the use of mineral fertilizers would mean a further decrease in GHG emissions (i.e. a reduction in the use of fossil fuels during manufacturing and transportation of those fertilizers). The treatment would also inhibit the germination of weed seeds present in manure (Sarapatka *et al.*, 1993), minimizing the use of herbicides. The final benefit, and the most important one in this case, is that the design of the system allows a substantial reduction in GHG emission from manure. The airtightness of the tank required to maintain anaerobic conditions in the digester completely eliminates atmospheric emissions of CH_4 during the treatment period. Subsequently, when the treated slurry is kept in long-term storage structures, the emission of CH_4 and carbon dioxide is reduced to a minimum because the organic matter has already been degraded. The use of the recovered methane will also mean less recourse to fossil fuels for energy on the farm, and a reduction in the GHG emissions associated with them.

2.3.2 Energy benefits of psychrophilic anaerobic digestion

In terms of energy, the treatment allows the recovery of substantial amounts of biogas with a high CH_4 content (60 to 85%). To compare with other fuels, 10 m^3 of biogas (65% CH_4) is the equivalent of 6 m^3 of natural gas, 8.5 litres of propane, 8 litres of butane or 6.5 litres of

gasoline (U.S. Department of Energy, 1996). The energy content of biogas containing 60 to 70% CH_4 is around 20 to 25 MJ/m^3 (Schafer, 1981), or nearly 20,000 BTU/m^3 (U.S. Department of Energy, 1995). This production of CH_4 by anaerobic digestion of an organic waste would benefit society by providing a clean fuel from renewable resources (Chynoweth *et al.*, 1997). Since the treatment is carried out at ambient temperatures and the manure does not have to be heated, all the biogas produced can be converted to energy which can be used on the farm. The biogas could be put to numerous uses such as space or water heating and steam production by direct combustion, production of electricity by cogeneration, and it could even become fuel for combustion engines. The U.S. Department of Energy (1996) has published a complete guide on possible uses of biogas. The energy recovery potential of the low-temperature treatment process is considerable. Estimates based on laboratory results show that the potential value of the energy recovered through the production of biogas from manure exceeds $100 million per year for Canadian farms.

The biotechnology of ambient-temperature anaerobic treatment is therefore a very efficient method of reducing the environmental and public health problems linked to the management of manure slurries. Since the treatment of manure slurry by low-temperature anaerobic digestion is very stable, is simple and inexpensive, does not interfere with regular tasks, recovers a substantial amount of energy, has proven especially effective in reducing odours and the pollution load, and eliminates CH_4 emissions, its use in small and large animal production operations would be highly justified. The process developed also takes into account current limitations on typical farms, such as those relating to capital, energy and labour. The installation of SBRs would be an asset for the sustainable development of the agricultural industry in Canada. However, it is essential that research be continued to ensure that operations are as satisfactory on a large scale as on the laboratory scale. Research is continuing in the laboratory and pre-industrial-scale units are currently in operation. The start-up of large-scale pilot units on the farm is planned for the medium term.

2.4 Research and development

Certain sectors concerned with the reduction of GHG emissions from manure storage structures should be given priority by AAFC. To begin with, research should be continued to adapt the biotechnology to larger scales and ensure its effectiveness in animal production operations. It would also be important to quantify the reduction in GHG and odour emissions following treatment (i.e. during storage and when spreading). In addition, the improvement in agronomic quality of treated manure slurry must be assessed, and more detailed economic studies are required to determine the real benefits of applying this biotechnology. Moreover, the biotechnology would have to be adapted to the other by-products of animal production (manure from dairy cattle and veal calves). It would also be essential to continue the research to extend the potential applications of low-temperature anaerobic digestion to other sectors of the agri-food industry (treatment of waste water from slaughterhouses and of effluents from dairies, cheese factories and agricultural processing plants).

Another research path which should be considered by AAFC is the evaluation of the effects of placing covers on manure storage structures to reduce GHG emissions. The impact of such systems for confining gas emissions would have to be quantified in terms of their effect on the physicochemical properties of manure slurry, the reduction of odour and NH_3 emissions, and the possible increase in N_2O emissions in the field. The actual production of low-energy biogas (20% CH_4) under covers should also be studied to assess the possibilities of methane recovery either for energy production or simply for conversion to a gas with less potential for atmospheric warming (CO_2). In addition, it would be useful to confirm the effects of cooling manure slurry on gas emissions of all kinds (GHGs, NH_3 and odours).

CONCLUSION

The management and storage of manure inevitably contributes to the increase in concentrations of anthropogenic GHGs from agriculture. The most important GHGs released from manure are methane and nitrous oxide. The emission of N_2O occurs mainly from the soil, and its reduction involves better management of the application of organic and inorganic fertilizers. With regard to methane, there is enough information available to prove that the storage structures commonly used in the industrialized countries promote emissions and are major potential sources, despite the variability reported in the literature. If no mitigation action is taken to reduce GHG emissions from animal production operations, we will be facing an inevitable increase in the emission of these gases in coming decades. Effective technologies do exist, however, for minimizing CH_4 emissions and for recovering significant amounts of energy which can be used on the farm. Indeed, the anaerobic treatment of manure would seem to be an accessible method which would make use of the waste from animal production farms by converting it to a clean biological fuel while minimizing the harmful effects of such organic waste on the environment.

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